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Cellulosic biomass feedstocks and logistics for ethanol production†

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Abstract: The economic competitiveness of cellulosic ethanol production is highly dependent on feedstock cost, which constitutes 35–50% of the total ethanol production cost, depending on various geographical factors and the types of systems used for harvesting, collecting, preprocessing, transporting, and handling the material. Consequently, as the deployment of cellulosic ethanol biorefineries approaches, feedstock cost and availability are the driving factors that influence pioneer biorefinery locations and will largely control the rate at which this industry grows. Initial scenarios were postulated to develop a pioneer dry feedstock supply system design case as a demonstration of the current state of technology. Based on this pioneer design, advanced scenarios were developed to determine key cost barriers, needed supply system improvements, and technology advancements to achieve government and private sector cost targets. Analysis of the pioneer supply system resulted in a delivered feedstock cost to the throat of the pretreatment reactor of $37.00 per dry tonne (2002 $). Pioneer supply systems will start by using current infrastructure and technologies and be individually designed for biorefineries using specific feedstock types and varieties based on local geographic conditions. As the industry develops and cost barriers are addressed, the supply systems will incorporate advanced technologies that will eliminate downstream diversity and provide a uniform, tailored feedstock for multiple biorefineries located in different regions. Published in 2007 by John Wiley & Sons, Ltd.

Keywords: bioenergy; feedstock supply; biomass feedstocks; cellulosic biorefinery; cellulosic ethanol; alternative energy

From fields to fuel tanks

The economic competitiveness of cellulosic ethanol production is highly dependent on feedstock cost, which constitutes 35–50% of the total ethanol production cost,[1] depending on geographical factors such as the biomass species, yield, location, climate, local economy, and the systems used to harvest, collect, preprocess, transport, and handle the material.[2] Consequently, as the deployment of cellulosic ethanol biorefineries approaches, feedstock cost and availability are the driving factors that influence the selection of pioneer biorefinery locations, and these same factors will largely control the rate at which this industry grows.[3] Due to geographic variability and complex distributed supply system dynamics, estimating feedstock costs and supplies has been a major source of uncertainty.

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This paper presents an integrated analysis of current feedstock supply system technologies in order to understand the current cost of delivering cellulosic feedstocks to a biorefinery. A pioneer supply system design is presented to demonstrate the current state of technology. Based on this pioneer design, a discussion of advanced technologies is given to identify key cost barriers, supply system improvements, and technology advancements necessary to achieve government and private sector cost targets.

This perspective is largely drawn from a number of recent reports.[1–6]

Feedstock supply system engineering starts at the biorefinery

Cellulosic feedstocks show great promise for technological advancement as an economically viable source for transportation fuel.[2] They are abundant and can be converted into fuels and chemicals by either biochemical or thermochemical processes, but the best efficiency may come from integration of both processes.[1] In order to understand the issues impacting feedstock costs, it is helpful to first understand the processes for converting cellulosic feedstocks to ethanol and other fuels and products.

Biochemical conversion process

Cellulosic biochemical conversion technologies, like grain ethanol processes, ferment sugars from the carbohydrate fractions of biomass into ethanol and other products. In grain ethanol processes, the fermentable glucose monomeric sugars are liberated from the grain starch, whereas, in cellulosic processes, the fermentable sugars are liberated from the cellulose and hemicellulose cross-linked polymeric molecules that make up plant cell walls.[4] Unlike starch, which is easily broken down into monomers, or simple sugars, the combination of cellulose and hemicellulose embedded in lignin forms a recalcitrant matrix analogous to rebar in concrete. This cellulosic matrix requires additional processes and technologies to liberate the sugars. Converting cellulose and hemicellulose to sugars can be accomplished either by acid hydrolysis or by pretreatment and enzymatic hydrolysis.[7] While both approaches are feasible, recent advances in cellulase enzyme technology have greatly improved the economics of enzymatic hydrolysis processes for converting cellulosic biomass to monomeric sugars.[8]

Thermochemical conversion process

Thermochemical conversion technologies, including gasification and pyrolysis, heat biomass feedstocks under low oxygen conditions to produce products that can be converted into various biofuels and biochemicals.[5] The gasification process limits the oxygen to about one-third of that required for burning. Under these conditions, synthesis gas, or 'syngas,' is formed, which is made up of a mixture of carbon monoxide and hydrogen.[5] This mixture can then be used directly as a fuel or converted into other fuels and chemicals. By further limiting the oxygen during heating, pyrolysis occurs, where the biomass is liquefied to a bio-oil that can be used directly as fuel or converted into other fuels and chemicals.[5]

While biochemical technologies are well-suited to converting biomass carbohydrates, thermochemical technologies are very effective at converting non-carbohydrate biomass fractions and consume all components of biomass with nearly equal efficiency and effectiveness.[4, 5] Analysis of both conversion processes has shown that thermochemical technologies can achieve ethanol production cost targets comparable to biochemical technologies.[1] Likely biorefinery designs will include integrated (hybrid) systems where thermochemical processes using non- or low-carbohydrate biomass will provide heat, power, and synthesis gas as add-ons to biochemical processes converting starch and/or cellulosic carbohydrates.[1]

Lignocellulosic feedstock supply system challenges

Economic development planners, commodity leaders, and others are assessing their regions to define how and when their areas can become part of the industry, which is largely determined by the location of the biorefinery. Because of economic risk, the first, or pioneer, biorefineries will rely on existing feedstock types, growing conditions, and the grain commodity infrastructure as the basis of their feedstock supply systems, as exhibited by the biorefinery designs of the US Department of Energy commercial-scale facility solicitation winners.[9] The supply systems for these facilities will be unique to each biorefinery as regional biomass variations, cropping practices, and equipment require optimization for relatively small, local areas. Thus, biorefineries will begin processing ethanol in limited areas and spread as feedstock production systems, based on advanced feedstock supply

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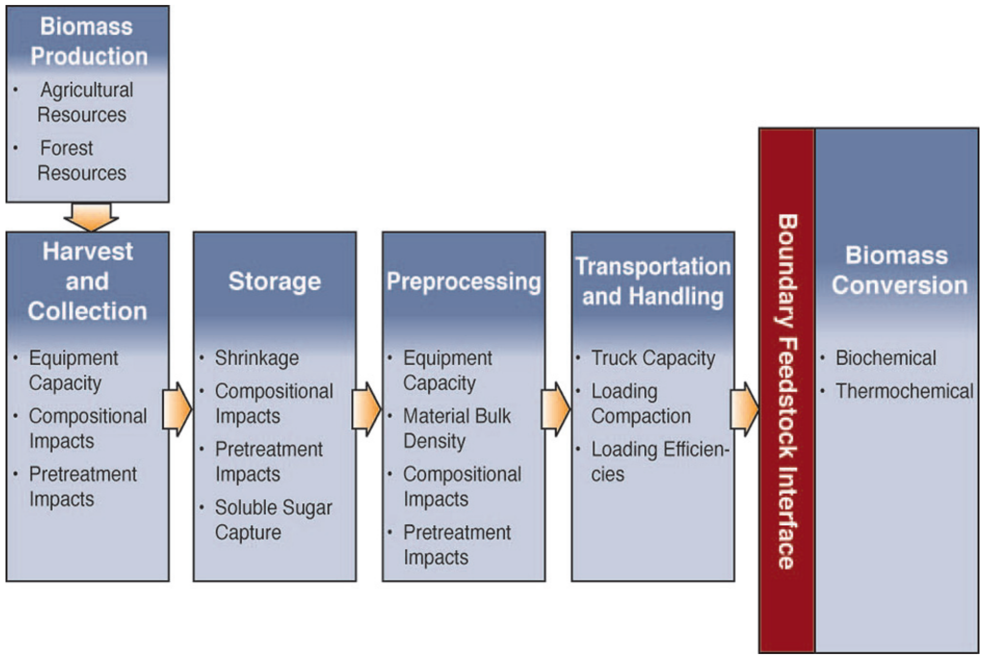

Figure 1. Feedstock supply system unit operations and barriers.

system technologies, begin supplying large enough quantities to enable them to be cost effectively replicated.

Supply system costs, which include all expenses associated with harvesting, collecting, storing, preprocessing, handling, and transporting biomass to the biorefinery (Fig. 1), face significant logistical and, more importantly, feedstock diversity challenges. These challenges prohibit the near-term establishment of a consistent and uniform biomass supply system. By shifting preprocessing from inside the biorefinery gate to the storage location, the complexity of receiving multiple formats (round or square bales) is eliminated at the biorefinery.

The costs that make up the minimum price at which cellulosic ethanol is sold, assuming no government incentives, can be roughly divided into feedstock costs and conversion costs. Using the dilute acid biochemical conversion process as the model, it is anticipated that pioneer commercial biorefineries will be able to devote about 35% of the Minimum Ethanol Selling Price (MESP) to feedstock purchase and supply.[4] Future technology advancements are projected to reduce biomass processing costs, which will, over time, provide increased purchasing power for biorefineries to access higher-cost biomass feedstocks.[1]

The feedstock portion of the cost can be divided into three categories: (1) *Grower Payment* – payment to the grower, which includes appropriate production costs and all other expenses related to the biomass value standing on the stump or in the field; (2) *Efficiency/Capacity* – overall supply system engineering and logistics costs, which include equipment, labor, and consumables; and (3) *Quality* – biomass cost adjustments (positive or negative) based on composition, BTU content, moisture, and particle size distribution. The efficiency and capacity dynamics for individual supply system unit operations are described in greater detail by Hess *et al.*[6] These categories are shown in Eqn (1), where \$/tonne is the cost to the throat of the conversion reactor at the biorefinery.

$$\$ / tonne = GrowerPayment\ [\$ / tonne] + \frac{Efficiency\ [\$ / hr]}{Capacity\ [tonne / hr]} + Quality\ [\$ / tonne] \quad (1)$$

The focus of the pioneer feedstock supply system design presented in this paper is the efficiency and capacity portion of the equation, which includes all expenses related to the engineering systems (equipment) necessary to move the feedstock from the production location to the biorefinery. Although these parameters can vary according to biomass varieties, yield, climate, local economy, and the specific engineering systems used, they are definable through manufacturer data and can be estimated with ag-economic equations. Based on technology advances, these parameters are predictable using research and development data, such as time-in-motion studies.[6]

Biomass feedstocks used in the supply system can be classified into one of three types: (1) dry herbaceous, which includes agricultural residues and herbaceous energy crops with less than 15% moisture (in general, dry herbaceous feedstocks are considered to be those with a moisture content <15%, although a few dry feedstock supply system configurations can process feedstock with as much as 20% moisture); (2) wet herbaceous, which includes agricultural residues and herbaceous energy crops with greater than 50% moisture; and (3) woody, which includes forest residues, forest thinnings, and fast growing woody sources.[1] These types and specific varieties (wheat straw, corn stover, switchgrass, forest residues, etc.) dictate the feedstock assembly system design and ultimately determine the engineering needs and constraints of the system.

Each unit of operation in the system also has distinct engineering and infrastructure constraints that affect costs. Addressing these constraints requires development of a baseline cost and logistics scenario for each major geographical region and its respective biomass types. Thus, supply system logistics and diversity are dependent on four major factors: feedstock type, variety, location, and the quantity of biomass passed through the supply system. The following section describes a single assembly system scenario based on a pioneer plant concept that relies on current technology only and uses one feedstock type (dry herbaceous), one variety (wheat straw), one location (western high desert, USA), and one quantity (726,000 tonnes delivered to the biorefinery).

Supply system technologies today and tomorrow

Pioneer feedstock supply system

Based on the average annual straw usage per animal and size of the Idaho dairy industry, an estimated 350 000 to 450 000 tonnes of straw are currently harvested annually for livestock.[10, 11, 12] While this large crop residue biomass market provides an excellent feedstock baseline model, it also demonstrates that biorefineries are not the only potential large users of biomass resources. Duane Grant, a south-central Idaho straw broker, reported that the 2004 value of straw in the Idaho dairy market was \$35 to \$46 tonne^{-1} delivered to the dairy. The price to the grower was dependent on proximity to the purchasing dairy but typically ranged between \$21 and \$31 tonne^{-1} baled and stacked on the roadside at the farm. For high quality straw, or in years that alfalfa is in short supply, straw market values as high as \$66 per tonne delivered to the dairy may occur (Grant D, 2004, pers. commun.).

For the models presented in this perspective, the 2004 incremental merchandising costs for the straw dairy market are estimated to include a raw straw purchase of \$4.20 to \$6.30 tonne^{-1} (laying in the field), a baling charge of \$16.75 to \$19.00 tonne^{-1}, a roadside stacking charge of \$4.40 to \$6.00 tonne^{-1}, and a transportation and handling charge of \$11.00 to \$13.20 tonne^{-1} for up to 113 km, plus \$0.07 tonne^{-1} km^{-1} over 113 km. The raw straw purchase represents the first part of Eqn (1), *the grower payment,* while the baling, roadsiding, and transportation costs represent the second part of Eqn (1), *capacities and efficiencies of equipment.* These figures do not include a quality cost; rather the material is either accepted or rejected. Using these costs as a baseline for comparison, the cost of INL-developed pioneer and advanced feedstock supply system designs are estimated using American Society of Agricultural and Biological Engineers methodologies, which capture all capital recovery, operating, and labor costs for each piece of equipment used in the supply system design. Details of the logistics and analysis of a pioneer supply system are discussed by Hess *et al.*[6]

Production

While different feedstocks have different average values, the grower payment can vary from less than \$11 dtonne^{-1} to \$44 dtonne^{-1} or more (dtonne denotes tonne dry weight).[13] The specific reasons for this variability are as diverse as the geographic regions and growers producing the biomass. However, the single largest variable affecting the feedstock value is tied to the tonnage demanded for energy production with respect to other demands, which include competing markets as well as soil/agronomic sustainability. These factors affect the grower payment and account for the \$11 to 44 cost variation.

Table 1. Baling operation logistics and cost summary.

Bale moisture, %			15
Baling window (hours/days/weeks)			12/6/6
Labor schedule (number of shifts - hours/shift)			2 – 7
Baling costs / *Tractor and large balers*	Qty.	% Util.	\$ dtonne^{-1}
01 John Deere 8230 180 kW (150 PTO kW)	286	100	Included with baler
01 Hesston 4910 Lg Sq 1.2 m × 2.4 m	286	100	12.80
Total weighted baling costs			12.80

Table 2. Field-side stacking operation logistics and cost summary.

Average haul distance (km)			0.8
Square bales – tonnes			804,000
Collection window (hours/days/weeks)			12/6/6
Labor schedule (number of shifts - hours/shift)			2 – 7
Collection costs / *Self-propelled bale hauler-stackers*	Qty.	% Util.	\$ dtonne^{-1}
01 Stinger Stacker 6500	80	100	1.70
Total weighted stacking costs			1.70

Harvest and collection

In a feedstock assembly system where a commodity grain is the focus of the harvest and collection operation, growers will be responsible for the timing and logistics associated with equipment and labor resources. They will identify who will perform the labor (themselves or a custom operator), when the harvest will occur, and where the commodity will be sold. They will also be responsible for baling and roadsiding the resulting straw. Because grain will remain the primary commodity, at least until the cellulosic biorefinery industry matures, the grain is assumed to bear all of the costs of the harvesting operation.[6] Thus, the costs and logistics associated with the feedstock assembly system begin with the collection of the straw lying in the harvester-produced windrow, where it is allowed to dry to a moisture content of 15% or less.

Collection of the windrowed material will be accomplished with balers that produce 1.2 m × 1.2 m × 2.4 m large rectangular bales. This bale size is recommended for the feedstock assembly system because it requires little infrastructure change in the scenario region, provides a relatively efficient roadsiding and storage configuration, and, most importantly, allows for the most cost-effective means of transporting the material due to its shape and packing. Table 1 shows the logistical data and cost per dry tonne for the baling unit operation, including capital, maintenance, ownership, fuel, twine, and labor.

The common practice for moving bales to the side of the road (roadsiding) involves using a loader and flatbed truck. The loader places the bales on the truck in the field, the truck drives to the stack location, and a loader moves the bales from the truck to the stack. However, INL studies show efficiency improvements to this operation by using a self-propelled loader/stacker to move the bales from the field to the stack. These systems have the capability of picking up bales at on-the-go speeds of 4.8 to 8.0 kph, and carry up to eight bales at a time. Table 2 shows the logistical data and cost per dry tonne for the roadsiding operation.

Storage

Biomass feedstocks, which have a relatively narrow harvest window compared to the year-round supply requirements of the biorefinery, will need a form of intermediate storage. Ideally, this storage would preserve the feedstock so that it enters and leaves as unchanged as possible. Therefore, the objective of the storage operation is to minimize any negative feedstock alterations that might occur at the lowest cost possible (including cost incurred from losses).

Major considerations for dry storage systems include overall gross shrinkage (dry matter loss), biomass material degradation leading to mass without yield (biological shrinkage), and other value-added changes. The key factor for controlling biological changes is low moisture (i.e. less than 15%) as the material enters storage and protection from moisture throughout the storage period. Outside storage of dry biomass is highly region-specific due to varying humidity and precipitation levels.

Thus, the cost of storage is simply the product of dry matter loss (%) and the total collection cost (baling and roadsiding), land rent or a grower storage fee, and a management fee (could be part of the land rent or storage fee) to

Table 3. Dry bale storage logistics and cost summary.

Bale moisture, %		15
Average tonnes stored per site		450
Annual precipitation, cm		21
Storage dry matter losses, %		5.00
Min. separation per insurance, m		30
Land rent cost, \$ ha^{-1} year^{-1}		310
Management cost per tonne, \$		0.48
Insurance cost per tonne, \$		0.52
Storage costs	% Util.	\$ dtonne^{-1}
Storage format		
01 Field stack	100	4.90
Storage cover		
00 None		
Total weighted storage costs, \$		4.90

maintain access to the stack at the time of use. An access perimeter should be included around each stack, particularly as it pertains to the fire code, when calculating the land rent. If moisture mitigation is needed (tarping, bale wrapping, etc.), the applicable machinery capital costs, labor costs, and material costs are added to the base storage costs. Table 3 shows the logistical data and costs associated with dry storage.

Preprocessing

In order to accomplish the needed size reduction and higher bulk density of the feedstock, baled biomass will be ground at the stack locations. A bale loader will move the bales from the stack to a mobile grinder positioned nearby. The ground feedstock will be conveyed into a truck as it is discharged from the grinder.

Analysis shows that minimizing grinder downtime when moving from one site to the next can have a significant impact on preprocessing costs.[6] For optimized scheduling, the stack sizes must be scaled according to grinder capacity and field yields, which may require combining stacks from different fields to a more centralized location. The number of trucks and the cycle time required to move the ground biomass to the biorefinery is highly dependent on the total capacity of the grinder(s) at each preprocessing location. Analysis of preprocessing and transportation unit operations must be integrated to optimize this process. Table 4 shows the logistical data and costs for the preprocessing operation.

Table 4. Preprocessing logistics and cost summary.

Preprocessing window (hours/days/weeks)			13/6/52
Labor schedule (number of shifts - hours/shift)			2 – 8
Preprocessing costs	Qty.	% Util.	\$ dtonne^{-1}
Self-propelled bale loaders			
01 Caterpillar TH220B Telehandler	12	100	1.60
Grinders			
01 Diamond Z 1352L Tub Grinder	12	100	4.70
Total weighted grinder costs, \$			6.30

Transportation and handling

Transportation systems are largely fixed with well-understood configurations and volumes that comply with state and local road laws. Thus, the primary constraints on transportation are (1) maximized truck cycle capacity (i.e. increasing the bulk density of the transported feedstock), and (2) maximized truck unit efficiency (i.e. optimizing truck routes and minimizing wait times). Understanding these constraints and their relationship with other unit operations is key to minimizing the costs associated with moving the biomass within the assembly system.

The feedstock handling and queuing systems at the plant include all handling operations necessary to unload the feedstock from the trucks, move it to interim storage, and insert it into the conversion process. The main considerations for identifying the necessary equipment are feedstock format, infeed rate, bulk density, and feedstock flowability. Currently, the most efficient way to move large quantities of bulk material on-site is by conveyor. Thus, conveying systems are used to transfer the feedstock from the trucks to interim storage and then into the conversion process. However, significant challenges are associated with this operation, primarily the low bulk density of the feedstock, which requires very large volume flow rates to maintain the capacity of a moderately sized (>1500 tonnes day^{-1}) biorefinery.

In order to meet the volumetric flow rate requirements with standard conveying systems, four unloading pits feeding two separate conveying systems are needed. As the feedstock is discharged from the truck, it is conveyed from the pit to a bucket elevator and then to a horizontal conveyor that feeds the storage bin. All conveyors are enclosed for dust, moisture, and wind control. The horizontal conveyors are en-masse drag conveyors. The handling system consists of grain handling equipment, but because this equipment is designed for handling grain at 650–800 kg m^{-3}, the conveyor speed analysis is currently ongoing to determine the effectiveness of these systems for this application. The motors on these conveyors are oversized for handling this light material, and parameters such as conveyor speed and bucket configuration may cause handling problems. Table 5 shows the logistical data and costs for the transportation and handling operation.

The total annualized cost of each unit operation to supply 726 000 tonnes of feedstock is shown in Table 6. These costs provide an overall economic view of the feedstock supply system and help identify economic constraints that can lead to technical research paths. For example, baling is the most capital-intensive part of the supply system, which suggests there is the potential to influence costs through equipment design and operation logistics. Transportation and handling bear the highest labor cost, which promotes automation and higher equipment efficiencies and capacities.

Table 5. Transportation and handling logistics and cost summary.

Average haul distance (km)			76
Feedstock bulk density (kg m^{-3})			180
Unload time (min)			43.9
Queue wait time (min)			45.4
Transport window (hours/days/weeks)			13/6/52
Labor schedule (number of shifts - hours/shift)			2 – 8
Bulk transportation costs / *Tractor/Trailer Bulk Haulers*	Qty.	% Util.	\$ $dtonne^{-1}$
01 Kenworth T800 3-axle day cab	33		
Trinity Trailer “Eagle Bridge” 13 m, 2 m sides	66	100	7.90
01 3.4 m × 36 m, 90-tonne truck scale	1	100	0.10
01 700 m^3 pit hopper	4	100	0.80
01 Bulk handling en masse conveyor	10	100	0.40
01 15,000 m^3 Eurosilo	2	100	2.10
Total weighted bulk transport and handling costs			11.30

Advanced feedstock supply system

Harvest and collection

Advances in harvest and collection technologies will occur in three key areas: (1) selective harvest (removing select portions of the biomass based on sustainability and biorefinery needs); (2) single-pass or minimum-impact harvest; and (3) harvest and collection efficiencies. Improvements in these areas can significantly reduce overall supply system costs and provide greater access to biomass through increased producer participation. For example, harvest technologies that address soil quality concerns, such as nutrient/water retention, erosion, and compaction, while providing potential value-add to land-based products will motivate grower participation and access to biomass resources.

To realize advances in harvest and collection technologies, several research elements must be addressed with respect to machine performance (i.e. efficiency, capacity, and resulting biomass quality). These research elements include (1) developing harvest and collection methods for all resource types (wet, dry, and woody) to eliminate or reduce unit operations and balance sustainability,

Table 6. Itemized annual costs for all feedstock supply system unit operations.

	Baling	Field stacking	Storage	Preprocessing	Transportation & handling
Total capital investment (\$)	\$21,443,285	\$10,030,396		\$6,188,775	\$9,418,970
Depreciation costs (\$ $year^{-1}$)	\$2,384,736	\$731,207	\$1,932,291	\$1,001,018	\$2,583,448
Operating costs (\$ $year^{-1}$)	\$6,299,571	\$267,191	\$434,463	\$1,508,070	\$1,485,126
Labor costs (\$ $year^{-1}$)	\$590,522	\$273,227		\$2,083,535	\$4,180,951
Total annual cost (\$ $year^{-1}$)	\$9,274,829	\$1,271,625	\$3,530,753	\$5,867,914	\$8,249,524

agronomic concerns, and product-use demands; (2) quantifying and implementing biomass quality factors with respect to composition, contamination, bulk handling, and conversion characteristics; and (3) developing and testing innovative equipment designs that limit the effects of feedstock diversity on downstream operations, particularly the front-end handling at the biorefinery. Without these research elements, cost effective supply systems, available tonnages, and universal biorefinery feed systems remain restricted.

Storage

Feedstock shrinkage (or dry matter loss) is the primary constraint on feedstock storage systems. Shrinkage risks and mitigation strategies vary widely from region to region. In regions where humidity and rainfall and/or temperatures are low enough to prevent significant microbial damage, annual dry matter loss can be as low as 1%, but in wetter, warmer regions, dry matter loss may exceed 25%. To achieve government and private sector cost targets, INL estimates that dry matter losses must be less than 5% for all feedstock types. The research needs to meet this shrinkage target include (1) assessing different storage options with respect to dry matter losses, compositional changes, and functional sugar yield; (2) establishing baseline costs of storage systems at different scales to identify infrastructure needs, cost barriers, and implementation issues; (3) understanding soluble and structural sugar losses during storage and developing methods to reclaim these sugars within long-term storage and queuing at the plant; and (4) developing cost effective, large-scale bulk storage methods that improve downstream operations (i.e., preprocessing, transportation, handling, and plant processing).

Preprocessing

Significant design advances involving mobile preprocessing units will facilitate a transition from the current bale-based supply system to a more cost-effective bulk-flowable system. However, advances in preprocessing equipment capacity, feedstock bulk density, and feedstock quality are still needed. Direct cost savings to both the preprocessing operation and the transportation and handling operation will result from improved equipment capacity and product bulk density. Indirect cost savings may occur through separation methods that extend preprocessing beyond size reduction to include value-added product streams that have the potential to improve processing efficiencies in the biorefinery. Specific research needed to realize significant improvement in future preprocessing systems includes (1) developing preprocessing performance requirements for each feedstock type and variety, (2) developing the relationship between biomass structure and composition to assess quality-upgrade potential and to develop equipment and methods to achieve needed upgrades, (3) understanding and controlling biomass tissue deconstruction to optimize grinder performance, (4) integrating biomass deconstruction and rheological property characteristics with innovative bulk compaction methods to increase loose bulk density, and (5) understanding and controlling the bulk-flowable properties of ground biomass to minimize transportation and handling problems.

Transportation and handling

Transporting and handling methods are highly dependent on the format and bulk density of feedstock material, making them tightly coupled to each other and all other operations in the feedstock supply system. These operations can account for nearly 30% of the total annual cost of a feedstock assembly system. Unlike the other operations in the supply system, typical transportation and handling systems simply move the feedstock to the biorefinery with little opportunity to add value to the feedstock. Hence, minimizing these costs is critical for meeting established cost targets.

Regardless of the transport methods (e.g. truck, rail, or barge), bulk density and flowability are key technical parameters that must be addressed to decrease transportation and handling costs. As such, transportation and handling research and development require close coupling with other supply system operations that increase bulk density and improve flowability. Specific research needed to improve transportation and handling systems includes (1) understanding feedstock physical and rheological properties (including bulk density) to optimize handling and transportation efficiencies, and (2) evaluating new transportation and handling methods that can possibly eliminate the need for some types of equipment or provide value-add opportunities.

Achieving national biofuel goals requires feedstock supply system advancements

All of the operations in current feedstock supply systems are already functional today. These systems exist to supply virtually any cellulosic feedstock to a biorefinery facility, and most of the equipment is functioning in the forage, specialty crop, and/or forest products industries. As such, there are no shortages of conceptual designs for moving biomass feedstocks from the field to the biorefinery. Rather, the challenges for feedstock supply systems are to:

1. improve feedstock logistics, specifically the efficiency and capacity of feedstock supply systems unit operations; and
2. develop a uniform commodity-scale feedstock supply system that connects the diversity of cellulosic feedstocks to a standardized supply system infrastructure and biorefinery conversion processes.

The logistical issues of feedstock supply systems discussed in this perspective are reasonably well-understood, and it is generally recognized that supply system logistics must be improved. Collectively, the supply system activities of harvest, collection, storage, preprocessing, handling, and transportation, represent one of the largest challenges to the cellulosic biofuels industry. Feedstock production and logistics constitute 35% or more of the total production costs of cellulosic ethanol,[4,5] and logistics associated with moving the biomass from the land to the biorefinery can make up 50–75% of those feedstock costs.[6] The actual percentage depends upon a host of factors; however, logistical costs exceeding 25% of the total biomass value leave very little profit margin for biomass producers and biorefinery operators.[1]

Nevertheless, improving feedstock supply system logistics alone will not remove the most significant supply system barrier to achieving either the near- or longer-term cellulosic biofuel goals.[14,15] When looking beyond a single biorefinery to an industry of biorefineries and commodity-scale cellulosic biomass supply systems, site-specific supply system logistics solutions will not be viable. For industrial-scale efficiency in the feedstock supply system, biomass handling must be minimized, and the numbers of unique types of equipment necessary to transport the various forms of cellulosic biomass from the field or forest to the biorefinery must be reduced. For example, a bale-based feedstock system changes the biomass format at least three times from the field to the biorefinery (e.g., standing/fallen crop → bale → shredded bale).

Each biomass format (i.e. low density windrow, bale, and size-reduced bulk biomass) requires unique equipment that cannot be interchanged or used to handle other formats. To complicate the issue further, there are multiple bale formats with their own respective lines of harvesting and handling equipment. Similar examples can be cited for the woody resources, including equipment for handling round wood, wood chips, and slash bundles. Increasing feedstock bulk density and converting biomass to a standardized bulk-flowable form, as near to the feedstock source as practically possible, will not only simplify the diversity of supply system equipment, but can also improve the overall efficiencies of supply system logistics.[6]

National biofuel goals will not be achieved with multiple unique and site-specific supply system designs, nor will they be accomplished with complex designs requiring multiple sets of unique equipment. Achieving these biofuel goals can only be accomplished through development of a highly efficient commodity-like feedstock supply system consisting of modularized harvesting and preprocessing equipment that can be adapted to the diversity of feedstocks and yet connect to uniform commodity-scale receiving systems of 'standardized' and highly replicable biorefinery designs.

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